Fabricating Very Short Channels in Organic Field Effect Transistors by Dielectrophoresis Technique

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Abstract

Dielectrophoresis (DEP) is utilized for fabricating a short channel in organic field-effect transistors (OFETs) using single crystal rubrene flakes. We observed high yield assembly of rubrene flakes between source and drain electrodes using DEP, and also confirmed a typical transfer characteristics of OFETs with I_{on}/I_{off} ratio ~ 10⁴. This result means that very short organic semiconductor channels with a few micrometers length, which is ~1/10 of ones in conventionally fabricated OFETs, are achieved. Since the channel length is defined by the separation between DEP electrodes, the high yield assembly of single crystal rubrene flakes will have a significant impact for miniaturization of OFETs with high electrical performance.

1. Introduction

Since miniaturization of organic field-effect transistors (OFETs) leads to the improving electrical performance, such as operating frequency due to short channel effect [1], development of their fabrication process has attracted considerable attention. Especially, the channel length less than several micrometers is required for high-speed device such as display device [2]. However, present OFETs have a long channel length ($20 \sim 100 \mu m$)[3-5], because it is difficult to apply the conventional lithographic technique using organic solvents such as developer and remover for fabrication process. Generally, their devices are fabricated through top-contact process using shadow mask or ink jet methods in which device size is limited tens of micrometers.

In order to overcome this problem, dielectrophoresis (DEP) technique is utilized for fabricating a short channel in OFETs as a bottom-up process. DEP technique enables to trap various materials such as graphene oxide flakes [6] and particles between preformed electrodes by using conventional lithographic process. It expects that the channel length in OFETs is defined by the separation between DEP electrodes in addition to resist free for patterning organic materials due to the bottom-up process. We achieved to make high yield assembly of organic single crystal flakes between DEP electrodes by applying an ac voltage. We also demonstrate the transfer characteristics of the OFETs with the channel length of 2 μ m fabricated by DEP.

2. Experiments

Rubrene single crystal flake, which shows high carrier mobilities in semiconductor organic materials, is used as a target material in DEP assembly. Synthesis of the crystal is carried out using physical vapor transport method [7].

Figure 1(a) shows a schematic drawing of the DEP assembly set-up. Rubrene flakes are dispersed in water. The solution drops into a silicon rubber pool placed on the source-drain electrodes/SiO₂(280 nm)/Si substrate. For the efficient assembly, the electrodes are formed comb-like shape as shown in Fig. 1(b) [8]. Typical separation between source and drain electrodes is 2-10 μ m. DEP assembly are carried out by applying an ac voltage of 3 V_{p-p} with a frequency in the range from 1 kHz to 1 MHz.



Fig. 1 (a) experimental set-up for the DEP assembly of rubrene flakes. (b) Schematic illustration of electrodes design.

3. Results and discussion

Figure 2 shows optical microscope images of the comb shaped electrodes with the separation length of 2 µm after the immersion of the devices A and B in aqueous solution of rubrene flakes using the same silicon rubber pool. The assembly of rubrene flakes was observed at the device A when the applied voltage is 3 V_{p-p} with a frequency of 1 kHz. On the other hand, rubrene flakes were not much observed in the device B with no applied voltage in spite of the immersion in aqueous solution. This result means that rubrene flakes are efficiently trapped between electrodes by DEP force due to an ac electric field. Moreover, the assembly of rubrene flakes was not really observed when the applied ac voltage is 3 V_{p-p} with a frequency of 1 MHz. In this case, the DEP force is very small due to the high frequency, considering Clausius-Mossotti function as a basic theory of DEP [9].



Fig. 2 Optical microscope images of electrodes with the separation length of 10 μ m after the immersion of the devices A (V_{p-p}=3 V) and B(no applied voltage) in aqueous solution of rubrene flakes.

Figure 3 shows a size distribution of rubrene flakes between electrodes. Many rubrene flakes with the size in the range from 5 to 20 μ m are trapped at electrodes when the ac voltage is applied. However, there is no difference in amount of rubrene flakes with the size above 20 μ m between applied and no applied voltage. Considering that the separation between electrodes is 10 μ m, this result indicates that the size of the efficient assembled rubrene flakes is defined by the separation length.



Fig. 3 Size distribution of rubrene flakes between electrodes separated by $10 \ \mu m$ as channel length.

Figure 4 shows transfer characteristics of the OFETs with rubrene channel prepared by DEP. Here the channel length is 2 μ m. We confirmed a typical p-type channel and I_{on}/I_{off} ratio ~ 10⁴. Unfortunately, the value of the I_{on}/I_{off} ratio is insufficient as compared with that (~10⁶) measured



Fig. 4 Transfer characteristics of the OFETs with rubrene channel prepared by DEP.

from the OFETs using a single crystal rubrene channel in previous report [10]. The reasons why the low value was observed are as follows: (1) contact resistance between the rubrene crystal and electrode is high due to the bottom-contact in DEP fabrication, and (2) the channel material is composed of many single crystal rubrene flakes as shown in Fig. 2, and the assembly of the rubrene flakes including domain boundaries between them behaves like a polycrystalline. The rubrene polycrystalline thin film transistors show lower carrier mobility (~ $0.05 \text{ cm}^2/\text{Vs}$) [11] as a comparison with carrier mobility measured from OFETs with single rubrene crystal [7]. As a result, the domain boundaries between the rubrene flakes lead to the carrier scattering and a serious deterioration of the electrical performance. The improvements in the DEP conditions are necessary for contact resistance and trapping a single crystal rubrene flake between electrodes.

4. Summary

We report on the scale-down process of the OFETs using DEP. We achieved to fabricate the OFETs with a short channel length of 2 μ m, which is ~1/10 of ones in conventionally fabricated OFETs, and also confirmed the device operations. Since the channel length is defined by the separation of DEP electrodes and the channel materials are patterned through resist free process due to the bottom-up approach, this method has a great advantage for miniaturization of the channel length in OFETs.

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